Climate change and groundwater: a short review

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Abstract: There is a general consensus that climate change is an ongoing phenomenon. This will inevitably bring about numerous environmental problems, including alterations to the hydrological cycle, which is already heavily influenced by anthropogenic activity. The available climate scenarios indicate areas where rainfall may increase or diminish, but the final outcome with respect to man and environment will, generally, be detrimental. Groundwater will be vital to alleviate some of the worst drought situations. The paper analyses the main methods for studying the relationships between climate change and groundwater, and presents the main areas in which hydrogeological research should focus in order to mitigate the likely impacts.

This article has two aims. The first is to present a summary of the current knowledge of the relationships between climatic variations and water resources, with emphasis on groundwater. The second aim is to review the main issues that groundwater specialists will have to face and study in order to minimize the impact of climatic variation and to protect groundwater resources.

The climate has changed in the past, is changing presently and will change in the future. The scale of the fluctuations varies from hundreds of millions of years to decades or less (for example Huggett 1991; Goudie 1994; Issar 2003; Lamy *et al.* 2006; Yang 2006). The present climatic trend (i.e. a warming trend), which is no longer a hypothesis but a planet-wide observation, may correspond to a natural warming phase, probably at the scale of a few hundreds years, which began in the nineteenth century; the warming is being accelerated and increased because of the anthropogenic release of greenhouse gases from fossil fuels burnt during the last two centuries. The main concern raised by global warming is that climatic variations alter the water cycle; indeed, in many cases, the data show that the hydrological cycle is already being impacted (Dragoni 1998; Buffoni *et al.* 2002; Labat *et al.* 2004; Huntington 2006; IPCC 2007).

Today there is a very large consensus, supported by an impressive set of observations and analyses, that anthropogenic activity is the main factor causing the present global warming (Trenberth *et al.* 2006; Kerr & Balter 2007). However, the Intergovernmental Panel on Climate Change (IPCC), does not provide total certainty to this view, but only indicates a probability greater than 90% (IPCC 2007) and a few recent papers raise some doubts about the driving role of greenhouse gases (de Jager & Usoskin 2006; Stanhill 2007; Svensmark 2007). Indeed, a heated dispute is going on, as there is a minority of scientists who claim that the main reason for the present climatic behaviour is natural (sun variability being the most probable) and that, very likely, the future warming will be moderate (Essex & McKitrick 2003; Landscheidt 2003; Santer *et al.* 2004; Michaels 2005; Singer & Avery 2006; IDAG 2005; Shaviv 2005; Scafetta & West 2006; Zastawny 2006; Lockwood & Fröhlich 2007). This issue is critical, because the worst possibilities considered by the IPCC indicate that the temperature will rise by several degrees and the warm phase will last for centuries, with dramatic consequences beyond those that can reasonably be defined at present. In any case, today, there is an unanimous consensus on the forecast that the warming will persist for decades, no matter what action is taken (Michaels 2005; Singer & Avery 2006; Trenberth *et al.* 2006; IPCC 2007). As the warming process continues, it will bring about numerous environmental problems, among which the most severe will relate to water resources (Loáiciga 1996, 2000; Milly *et al.* 2005; Holman 2006; IPCC 2007).

The magnitude of future consequences can be inferred from the dramatic effects caused by the natural and 'moderate' climatic changes that occurred during the last millennium, during which millions of deaths all over the world were caused directly by the alternation of droughts and short cool–warm periods (Lambe 1977; Goudie 1994; Dragoni 1998; Brown 2001; Fagan 2001; Davis 2002). The development (and in some cases the

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disappearance) of many civilizations was determined by natural and 'moderate' climatic change (Stewart 2005; Brooks 2006; Cremaschi *et al.* 2006; Kumar *et al.* 2006; Issar & Zohar 2007). Clearly a comprehensive knowledge of climate variations in space and time is vital in order for human society to adapt and survive. The key issues in the study of climate change (Oldfield 2005) are:

(i) what will be the amplitude and rate of global climate change over the next century and beyond;
(ii) how will the global mean climate be expressed in terms of extreme droughts and floods, sea level changes, groundwater recharge, soil degradation, deforestation, loss of biodiversity, and changes in ecosystem functioning, especially in view of the human-induced greenhouse effect; and
(iii) how do the complex changes involved affect the key issues of vulnerability and sustainability of water resources for the human population in general and groundwater in particular.

The importance of the relationship between groundwater and climatic change cannot be overstated. The global volume of groundwater is estimated at between 13% and 30% of the total volume of fresh water of the hydrosphere (Jones 1997; Babklin & Klige 2004) and groundwater provides 15% of the water used annually (Shiklomanov 2004*b*), the remainder being from surface water. Aquifers mitigate droughts as they have a high storage capacity and are less sensitive to climate change than surface water bodies. Surface water baseflow is, of course, groundwater discharging from store.

General observations regarding scenarios, future climate and water resources

The IPCC prepared five reports, the latest of which, in a preliminary version, was released in January 2007. The conclusions of this report most relevant to water resources and groundwater are (IPCC 2007):

- Projected warming in the twenty-first century shows geographical patterns similar to those observed over the last few decades. Warming is expected to be greatest over land and at the highest northern latitudes, and least over the Southern Oceans and parts of the North Atlantic Ocean;
- Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions;
- The more optimistic globally averaged rises in sea level at the end of the twenty-first century are between 0.18–0.38 m, but an extreme scenario gives a rise up to 0.59 m;
- It is very likely that hot extremes, heat waves and heavy precipitation events will continue to become more frequent; and
- Increases in the amount of precipitation are very likely at high latitudes, whereas decreases are likely in most subtropical land regions.

The IPCC scenarios (global and regional) are based on the results from Global Circulation Models (GCMs), traditionally considered by the IPCC to be the most reliable tools for obtaining indications regarding the future climate (Troen 1993; Kattenberg *et al.* 1996; IPCC 2007). Uncertainties conspire to make the model output, a rough approximation at best, of what could happen under various assumptions of greenhouse gases emissions (Covey 2003; Friedlingstein *et al.* 2003; Bender *et al.* 2006; Hegerl *et al.* 2006; Schmidt *et al.* 2004; Masson-Delmotte *et al.* 2006; van Ulden & van Oldenborgh 2006; Zhang *et al.* 2006; IPCC 2007; Schneider 2007). Future scenario outputs may even be contradictory (Rosenberg *et al.* 1999; Gagnon & Gough 2005; Stephenson *et al.* 2006; IPCC 2007; Kripalani *et al.* 2007; Li *et al.* 2007) and the results are averages over vast areas (IPCC 2007; Jacob *et al.* 2007; Ruosteenoja *et al.* 2007). By using Regional Circulation Models (RCMs), nestled within a GCM, one can arrive at averaged results (in terms of rainfall and temperature) for areas as small as 600 to 2500 km^2, but the results often depend more on the choice of the initial GCM than on the choice of the emission scenarios (Hay *et al.* 2006; Graham *et al.* 2007; Ruosteenoja *et al.* 2007; Olesen *et al.* 2007). This is unsatisfactory for defining the impact of climatic variations on water resources, and for planning intervention strategies for mitigating the likely impacts.

The inadequacy of the GCMs suggests that other approaches, although empirical, should be used together with the GCMs. The 'analogue approach' gives information that is more specific than that given by the GCMs by reconstructing past climates (i.e. temperature and precipitation) in a given area. These reconstructions can be used to construct future scenarios by analogy. The analogue approach assumes that, if a given average temperature variation corresponded to a given variation in rainfall or in water resources in the past, a similar temperature variation in the future will cause similar effects. Thus it is accepted that this occurs regardless of the causes of the variations in temperature, which may also be of different types, such as variations in the solar constant or the concentration of greenhouse gases in the atmosphere. This assumption can only be maintained if the temperature variations being compared are similar and if they occur during similar atmospheric boundary conditions, i.e. during time periods in which the planet has cryosphere, oceans and land masses in similar conditions (Wigley *et al.* 1986; Dragoni 1998). Similarity can be accepted only if the 'palaeoanalogue periods' go back no more than a few millennia or, on a more detailed scale, if the palaeoanalogues consist of multi-annual instrumental series, such as those of the warm years at the beginning and the end of the twentieth century. Of course the future scenarios based on such palaeoanalogues are not quantitatively sound, and cannot be extrapolated confidently into the future beyond a few decades. Thus, despite the progress made by GCMs and by information obtained by the analogue approach, it must be recognized that a definition of scenario given about twenty years ago is still valid: 'scenarios are not meant to be predictions of future climate; rather they are meant to be internally consistent pictures of a plausible future climate, a basis for other workers to evaluate the possible impacts of climatic change on Man and society' (Wigley *et al.* 1986).

Data and information on past climatic and hydrological conditions are important for verifying whether a GCM or RCM is potentially reliable: only a model that provides good results for the present and/or for past climate can be reliably used for constructing future scenarios (Bell *et al.* 2003; Karl & Trenberth 2003; Dearing 2006; Sloan 2006).

Confidence is increased if one or more models and the analogue approach independently indicate a similar future scenario in terms of temperature and rainfall. Nevertheless, the actual intensity and spatial and time variability of rainfall and temperature for a given scenario and a given region still remain uncertain. The same degree of uncertainty is retained when translating rainfall and temperature to evapotranspiration, runoff and aquifer recharge, whatever procedure is adopted (Strzepek & Yates 1997; Di Matteo & Dragoni 2006).

Another consequence of the uncertainties intrinsic to the climatic scenarios is that the impact of the conditions provided by the scenarios on hydrogeological systems are tentatively simulated for different, and more or less arbitrary values for the climatic factors (Rosenberg *et al.* 1999; Loáiciga *et al.* 2000; Taeuea *et al.* 2000; Nijssen *et al.* 2001; Yusoff *et al.* 2002; Allen *et al.* 2004; Gagnon & Gough 2005; Jha *et al.* 2006; Vicuna & Dracup 2007; Olesen *et al.* 2007). The results provided by this approach show the most probable direction of change, the sensitivity to different factors which regulate hydrological systems, and point to the processes which will be modified most by future climate variation.

Main tools to study the relations between groundwater and climate variations

General considerations

A good knowledge of the geology and hydrogeology of the study system is an essential prerequisite to investigating the impact of climate change. Ideally, the study of groundwater resources should be based on a reliable, continuous and dense database of hydrometeorological data and soil moisture, covering a long time interval. These data should be coupled with a large amount of spatially distributed quantitative information such as hydraulic conductivity and porosity. However, adequate data are rarely available and work is often qualitative. Thus a high quality network of data collection needs to be established. The networks are essential not only to evaluate the present situation but also to follow the evolution of the processes and, therefore, to validate the knowledge gained through time. Natural experimental systems, not directly influenced by anthropic activities (in terms of variations in the use of the land or irrigation) may be used to isolate, at least locally, the effects of climate variation from those derived by Man's presence. Management of water resources has brought, even on a regional or continental basis, significant variations (Vörösmarty *et al.* 2004; Shiklomanov 2004*a*).

Remote sensing provides a convenient way of assessing the spatial and temporal variations in water fluxes in different components of the water cycle. Attempts to estimate small scale temporal changes in the gravity field due to redistribution of water are in progress. The GRACE (Gravity Recovery And Climate Experiment) satellite is aimed at observing the gravity field to a high accuracy (*c.* 1 cm in terms of geoid height and a spatial resolution of 200–300 km). Any redistribution of water masses in different parts of water cycle may result in time variation of gravity field.

Numerical hydrological and hydrogeological models, in spite of being a simplified representation of reality, are invaluable tools for describing and understanding hydrogeological processes. The model serves both the understanding the system and prediction, once the model is validated and calibrated using historical data. Models should ensure internal consistency, compatibility with uncertainties, compatibility with constraints of data and robust performance (Oldfield 2005). In order to assess the effect of climate on a particular groundwater system, dedicated monitoring of various parameters is required. There are many modelling codes for flow in both the unsaturated zone and the saturated zone and various water quantity and quality issues can be accounted for depending upon the boundary conditions, subsurface properties and process representation. The models can differ in scale and in detail depending upon specific process (e.g. evapotranspiration or groundwater mass transport).

Isotope methods

During the last four decades, isotope methods have been developed which are based on proxy records of climate change in the past in different media, and such studies are termed as palaeohydrology/palaeoclimatic studies (Parrish 2001; Mazor 2003). The different media/materials through which climate change can be studied are:

(i) oxygen and carbon isotope composition of benthic and planktonic foraminifera (Bar-Matthews *et al.* 2003);

(ii) hydrogen and oxygen isotopic ratios of organic matter (Sauer *et al.* 2001; Shu *et al.* 2005; Webb & Longstaffe 2006);

(iii) ice cores (Thompson *et al.* 1998; Hondoh 2000; Thompson *et al.* 2000); and

(iv) carbon and oxygen composition of carbonates, cave deposits, lake, groundwater (Li *et al.* 1989; Bar-Matthews *et al.* 1998; Frumkin *et al.* 1999; Niggemann *et al.* 2003; Sasowsky & Mylroie; 2004; Pentecost 2005; Parker *et al.* 2006).

Most media are basically formed through precipitation which in turn originates or is modified by climatic processes, and these can be reconstructed on the basis of their isotopic composition, which in many cases provides some information about rainfall, aquifer recharge and the water table position at the time of deposition (Cremaschi & Di Lernia 1999; Nelson *et al*. 2000; Drake *et al.* 2004; Garnett *et al.* 2004; Mariani *et al*. 2007).

The vadose zone of an unsaturated aquifer contains information about climate change in the range of tens of years to thousand of years. This information is contained within the solute (chloride) and the ^{3}H, ^{2}H, ^{18}O profiles. In case of homogenous soils (without cracks and fissures) infiltrating water moves through the unsaturated zone by displacement (Zimmermann *et al.* 1967). Estimates of recharge using thermonuclear tritium peaks of 1963–64 have been made (Anderson & Sevel 1974; Sukhija & Shah 1976; Allison & Hughes 1978). Chloride profiles have also been used to measure mean recharge and residence time of water in vadose zone (Allison & Hughes 1978; Edmunds & Walton 1980; Sukhija *et al.* 1988; Lo Russo *et al.* 2003).

The residence time of a tracer in the vadose zone determines the number of years for which the climate information may be available. Cook *et al.* (1992) estimated the persistence time of isotopes before they are smoothed by diffusion and dispersion to vary from several years to 10 000 years. Climate fluctuations over 5–10 years are discernible in chloride profiles in regions like Cyprus (Edmunds & Walton 1980; Edmunds *et al.* 1982, 1988); however, two chloride profiles in Senegal (Edmunds *et al.* 1992) have a length of record of 30–50 years and exceptionally 475 years (at Longa). Attempts are in progress (Lal 2000) to study palaeoclimatic recharge during the last thousand years using ^{32}Si.

Impacts and adaptation: some topics on which to focus research

Impact of climate change on groundwater recharge and discharge

Any variation in the regime and quantity of precipitation, together with variations in temperature and evapotranspiration, affects groundwater recharge. In general, groundwater recharge will increase in areas where precipitation is increased and vice versa. Groundwater recharge will increase also in areas where permafrost thaws (Potter 2002; Kitabata *et al.* 2006). Most of the consequences of changes in recharge will be detrimental. There is general agreement that many areas of currently high precipitation are expected to experience precipitation increases, whereas many of the areas at present with low precipitation and high evaporation, now suffering water scarcity, are expected to have rain decreases (IPCC 2007; Issar & Zohar 2007). As conditions change rapidly, the existing infrastructure network will have to be reshaped rapidly (Potter 2002; Semadeni-Davies *et al.* 2007).

The groundwater recharge is the residual flux of water added to the saturated zone resulting from the evaporative, transpirative and runoff losses of the precipitation. It can take place by diffuse infiltration, a preferential pathway, and through surface streams and lakes. Thus groundwater recharge is a sensitive function of the climatic factors, local geology, topography and land use. Generally, measured groundwater recharge is a site specific quantity and this complicates the problem of defining its regional impact. The broad scenarios given by the GCMs should be considered only as a very preliminary basis for investigations to be carried out to understand the effects of the changing climate on groundwater. Any research on the variation of recharge has to be based on data and investigation specific to the hydrogeological system under consideration. These investigations must be based on detailed knowledge of the geological structures, and may involve the use of complex models which consider multi-component interaction, hydrological-atmospheric processes, hydrological boundary conditions and identification of model sensitivity to parameter uncertainty. In one way or another, the results given by the models must have some form of calibration, and this inevitably leads to using the known present or past conditions of the systems under investigation.

Generally, variations in aquifer recharge not only change the aquifer yield or discharge, but also modify the groundwater flow network, e.g. gaining streams may suddenly become losing streams, groundwater divides may move position.

The effects of recharge variation on groundwater flow has been considered by various authors, sometimes not within the context of seasonal variations in recharge. Meyboom (1967) has shown on a seasonal basis how the decrease or absence of recharge changes the flow relationships between recharge areas and shallow, contiguous lakes. An important paper by Winter (1999) shows how climatic conditions affect the direction of groundwater flow and the relationship between superficial hydraulic bodies and subterranean waters, at different scales. Cambi & Dragoni (2000) studied the effects of climatic variations on the Bagnara spring, located in the Umbria-Marche Apennines (Italy), in an area where both the analogue approach and the most recent GCMs forecast a decrease in rainfall and, therefore, of groundwater recharge (De Felice & Dragoni 1994; IPCC 2007). The Bagnara spring is located on the west slope of an asymmetric anticline (Mount Pennino Anticline), the core of which comprises permeable limestone and is bounded by a low permeability marl formation. The spring is located at the interface between the marl formation and the limestone. The recharge over the anticline core partly feeds the spring, and partly feeds a deeper, regional, flow (Fig. 1).

A numerical model was built and calibrated in different stages in order to quantify the possible effects of climatic variations on the Bagnara spring system. The simulations confirmed that if there is a decrease of recharge, the area feeding the spring shrinks, while the area feeding the lower regional flow system increases. This implies that any decrease in annual recharge will produce a larger decrease in the spring yield and to a smaller percent decrease of the regional flow. It may, therefore, be necessary to develop new techniques for capturing some of the water feeding the regional flow, before it reaches the polluted alluvial plains or deep evaporitic formations where salinization occurs (Cambi & Dragoni 2000).

In the areas already suffering from water scarcity and in those where the rainfall will decrease and the climate will get drier, it is crucial to try to increase recharge artificially. The techniques for the reuse and recharge of the aquifers by means of low-quality reclaimed water play a crucial role.

Groundwater discharge is another key element in the water cycle which includes loss of water from the aquifers to surface water, to the atmosphere and abstraction for human needs. The influence of the climatic changes on the discharge can be assessed by measuring, both spatially and temporally, the base flow to the rivers, lakes, wetlands and oceans and by studying the role of vegetation in transpiration.

Climatic change and fresh water discharges to the oceans. During the last decades it has been realized that the contribution of subterranean discharge of groundwater to the oceans is large, perhaps as

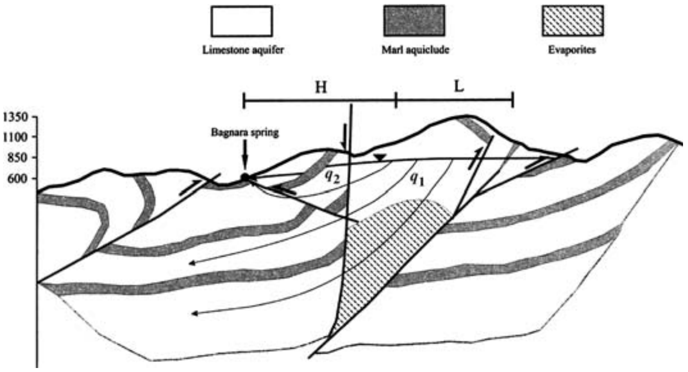

Fig. 1. Hydrogeological diagram of the Mount Pennino anticline and the Bagnara spring. Thick arrows indicate faults. Thin arrows indicate the flow path, towards the regional flow (q_1) and the spring (q_2). H, recharge area of the spring (flow towards the higher boundary); L, recharge area of the regional flow (flow towards the lower boundary). If the recharge decreases, H decreases and L increases, while the value q_2/q_1 decreases. Elevation is in metres above mean sea level, horizontal scale is equal to vertical scale.

much as 12 000 km^3/year (Speidel & Agnew 1988); a more recent review paper, presenting the methods for quantifying submarine groundwater discharge, indicates that the process is essentially ubiquitous in coastal areas (Burnett *et al.* 2006). All this water is lost to the sea, often of acceptable quality, and research to improve the measurement and recovery of it should be strongly enhanced.

Groundwater and reforestation. As trees are CO_2 sinks, reforestation coupled with new tree plantation has been considered key to maintaining control over CO_2 in the atmosphere (Schellnhuber *et al.* 2006; IPCC 2007). However, in forested areas, groundwater recharge is generally lower than in non-forested areas, and thus the water table and groundwater storage are generally lower (Scanlon *et al.* 2006). Recent research, based on computer simulations suggests that, despite carbon dioxide absorption, reforestation in high latitudes would help warming, because the tree would decrease albedo and increase evapotranspiration; conversely in the tropics the trees would have an overall cooling effect (Bala *et al.* 2007). These findings support the idea that tropical arid and semi-arid areas should, whenever possible, be reforested and afforested, as, according to some preliminary estimates, the sequestration of CO_2 could be in the range of 30–50% of industrial emissions (Issar 2006, personal communication). The water to carry on such activities should be provided by surface runoff, sewage from urban centres and, most important, by low quality, fossil groundwater, which is largely present in the arid and semi-arid areas of the world.

Climatic change, groundwater and landslides. The variations in the level of groundwater inevitably entail a variety of geomorphological and engineering effects. Slope stability is strongly influenced by the water pressure in pores and fractures and, therefore, by groundwater. In areas with increasing groundwater recharge, there will be increased slope instability. An inverse evolution would be expected in those areas in which recharge decreases. The relationships between all the factors which determine the stability of a slope, such as its geological set up, rock resistance, morphological situation, groundwater recharge, neutral pressure distribution and the quality of the climatic scenarios, are complex and spatially variable so that it is difficult to draw general conclusions, and research on the subject is relatively scarce (Dehn & Buma 1999; Dikau & Schrott 1999; Dehn *et al.* 2000; Malet *et al.* 2005; Dixon & Brook 2007). In an area around Bonn (Germany) a process-based, spatial and temporal model for groundwater variations and slope stability indicates that the most unstable conditions occurred during the transition from the more humid Little Ice Age to a dryer, recent climate (Schmidt & Dikau 2004). In the Italian Dolomites there appears to be a close correlation between landslides and climatic variations, to the extent that many of the identified and dated landslides can be considered as indicators of climatic change (Corsini *et al.* 2004).

Climatic change, groundwater rebound and sinkholes. In those areas in which mining activity was intense and where working mines required dewatering, a progressive groundwater rebound results when mining activities and pumping cease. Groundwater rebound, which may last for many years and involve very large areas, can cause problems of engineering stability and pollution (Banks & Banks 2001; Razowska 2001; Burke *et al.* 2005). Conversely, a fall in groundwater level may cause collapse of cavities with a roof close to the surface, and the formation of sinkholes. This risk is widespread in karst areas (Ford & Williams 1989; Waltham *et al.* 2004). The problems of areas with groundwater rebound and sinkholes should be tackled whilst bearing in mind future recharge variations as indicated by climatic scenarios.

Water scarcity and traditional techniques for water resource management. The problems of water shortage in arid or semi-arid areas have been tackled using traditional techniques in some areas (Pandey 2000; Radhakrishna 2004). These include water harvesting and use of qanats. Rainwater harvesting can be used to recharge groundwater via recharge ponds (Sukhija *et al.* 1997). Qanats are drainage tunnels commonly found in the arid and semi-arid areas of Europe, North Africa and Asia (Castellani & Dragoni 1997; Issar & Zohar 2007). The issue of the traditional techniques to face the present and future aridity is an important one, as these techniques allowed the survival of human populations in difficult areas and during changing climates in the past. However, these techniques are incompatible with intensive agriculture and a high population density. Moreover, qanats drain aquifers permanently, even during periods in which water is not needed. It is probable that in specific areas and with the use of present knowledge, these simple and low cost techniques can be revived and applied with much improved results.

Climatic change and groundwater quality. The climate is expected not only to affect input (recharge) and output (discharge), but also to influence the quality of the groundwater. For example, water recharged during an arid period may have a higher concentration of salts and hence higher TDS, while during a wet period the converse may occur (Sukhija *et al.* 1998). However, to appreciate such changes long-term monitoring of rainfall and groundwater quality is required. It is also possible to link the occurrence of certain ions in groundwater to particular water–rock processes that occurred during specific past climatic periods.

Final observations

Neither the impacts of climatic change on water resources nor the possibilities offered by groundwater to mitigate drought are new. What is new is the global dimension of the environmental change and its permanency. Compared to the climatic changes of the past, the present change is taking place in a world where many vast areas are densely populated, with a high water demand. Even if the climate were not to change, a water crisis will still occur. Increased average temperature during the last few decades overshadows the impact of anthropogenic activity and its impact on water resources which are larger than those caused by any recent past climate change (Vörösmarty *et al.* 2004; Bouwer *et al.* 2006). Indeed in many areas the lack of water reflects a decrease in rainfall (i.e. climatic change), but often the underlying reason is an increase in consumption (Falkenmark & Lannerstad 2005).

In order to overcome the present and future water and environmental problems it is necessary to try to predetermine the problems through focused research, based on a good set of meteorological and hydrological data, which at present are far from satisfactory. The protection and restoration of ecosystems that provide critical water resources, such as those protecting recharge areas, wetlands and mountain forests is critical. There is a need to reduce the gap between the water supply and demand with more efficient irrigation systems, training of farmers, recycling of waste water, water conservation through public awareness and groundwater legislation for better groundwater management. Another key point is international co-operation, both in research and in the rational distribution of water resources.

These actions are widely agreed by national and international bodies and by the agencies that work for the environment and water resources (Vrba & Verhagen 2006). Some of these actions, such as transboundary management of resources, are complex, and can only be implemented slowly. Installation of monitoring networks is less difficult provided the will is there, but data needs may never be satisfied (Vörösmarty & Sahagian 2000; Shiklomanov 2004*b*; Di Matteo & Dragoni 2006).

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